MACHINE DESIGN

Polyimide composites challenge metals

A variety of polyimide composite materials produce cost-effective alternatives to cast-metal parts.

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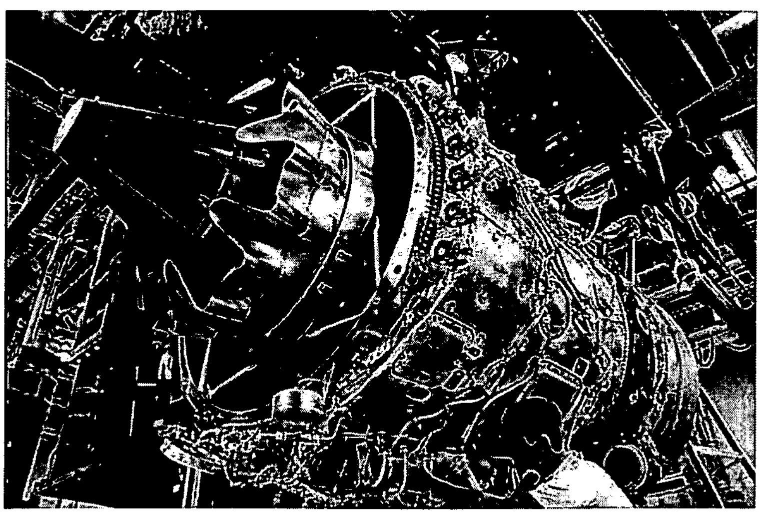
Aerospace companies often select new materials based on their ability to make designs simpler, more durable, easier to maintain, and more economical to produce. To meet these goals, designers have often converted cast-metal parts to those made from polyimide composites.

These materials have matured and are gaining wider acceptance in industrial and commercial applications. But unlike high-performance polymers that also developed through military programs, polyimide composites have been a tougher sell for commercial applications. Designers historically hesitated specifying advanced composites as metal replacements because their manufacturing processes are less mainstream and often more expensive than conventional polymers.

However, it's often these nonconventional manufacturing techniques that, when understood and employed early, give designers more freedom to customize the composite for an application. The fillers or fibers and polyimide matrix of advanced composites may be combined using a variety of fabrication processes. The combination generally depends on part count, size, and complexity, and the required physical or mechanical properties.



The bushings, bearing pads, and splines in the 10-stage, high-pressure compressor of the Rolls-Royce BR710 turbofan engine are made from Vespel® polyimide. These parts are exposed to temperatures up to 525°F yet need no lubrication.

This ability to selectively tailor composite constituents such as fillers of graphite and MoS_2 or reinforcement fibers is generally easier and more affordable than tweaking alloying elements in metals. For runs of 500 parts or less, machining stock shapes is one option. For larger volumes, and complex geometries, direct forming from sheet molding compounds (SMC) or new thermoplastic polyimide (TPI) composites can be cost effective.

A case in point

To see how composites can outperform metal, consider a tube clamp for an aircraft engine. The clamps attach hydraulic, hot air, and/or electrical lines onto the engine housing.

Clamp designs vary, but most have one bolting point and secure up to four tubes with diameters ranging from 0.25 to 2.0 in. Single-tube clamps usually bolt at the end and double-tube clamps at the center.

In all cases, bolt torque holds the tubes. This causes bending stresses to develop within the clamp next to the bolt. Misalignment of the tubes can intensify this static bending stress, so clamps must be built to tight tolerance.

Cyclic fatigue is another concern. Dynamic load from engine vibration, thermal growth of the long tubes, and large *g*-forces associated with military aircraft maneuvers all contribute to the problem. In addition, improper design of the clamp itself can cause unwanted wear on expensive tubing.

To help thwart wear, designers coat or sandwich intermediate materials between the surface of the tube and clamp. Clamps must also accommodate thermal spikes on the order of 700°F in the hotter sections of

Tips for machining polyimide composites

Composites are relatively easy to shape because they are inherently dimensionally stable at machining temperatures. Their inherent stiffness and mechanical strength also improve machinability. Standard metalworking equipment and techniques can produce parts to tight tolerances

Carbide tooling such as C-2 grade Kennametal K-11 and Carbaloy 895 is preferred when tool life is particularly important. Countersinks, end mills, and reamers made of high-speed steel are appropriate for short runs.

Circular saws can cut up to 3-in.-thick stock using a 10-in.-diameter "setless" 8 to 12 teeth/in. blade, operating at 6,000 to 8,000 ft/min with water coolant.

Sections as thick as 5 in. cut on a band saw without coolant with a sharp 10 teeth/in. blade with standard set. Thin sections require a finer blade, while special alloy blades work best for most filled compositions.

Close tolerances demand carbide-tipped tools and chip-breakers.

Tool cutting edges should be sharp, with a nose radius of about 0.003 to 0.008 in. Cutting speeds similar to those for machining brass help maintain dimensional stability.

Plastic composites are more elastic and have a higher coefficient of thermal expansion than metal and therefore have a greater likelihood of seizing when drilled. The following drills and drill modifications reduce the possibility of seizing.

Standard twist drills can handle holes up to half the drill diameter deep. Holes deeper than half a drill diameter are more prone to seizing and require modified drills.

Modified drills can feed at rates normally employed in cutting mild steel. Modifications include reducing the diameter along the full length of the drill body except for the leading ⅛ in. behind the lands and increasing lip to 25 to 30° versus standard 12 to 15°. Some advise thinning the standard drill web on drills 1 in. in diameter and larger.

For through holes, spade drills give better surface finishes and reduce chipping at the exit hole.

As with drilling, reaming requires modified tooling to avoid seizing. Reaming may produce a tapered hole 0.001 to 0.002 in. larger than desired due to temperature rises during the procedure. Boring the last 0.015 in. allows for closer tolerances. Deep, on-size holes can be reamed and bored like those in mild steels.

Shapes are ground to close tolerances on surface, double disc, or centerless grinders at a table surface speed of approximately 80 ft/min for rough cuts and about half that for finish grinding on surface grinders. A 12-in.-diameter 32A46-H8VG wheel works well at surface speeds of 3,000 to 4,000 ft/min. The wheel should be diamond dressed as for finish grinding of steel.

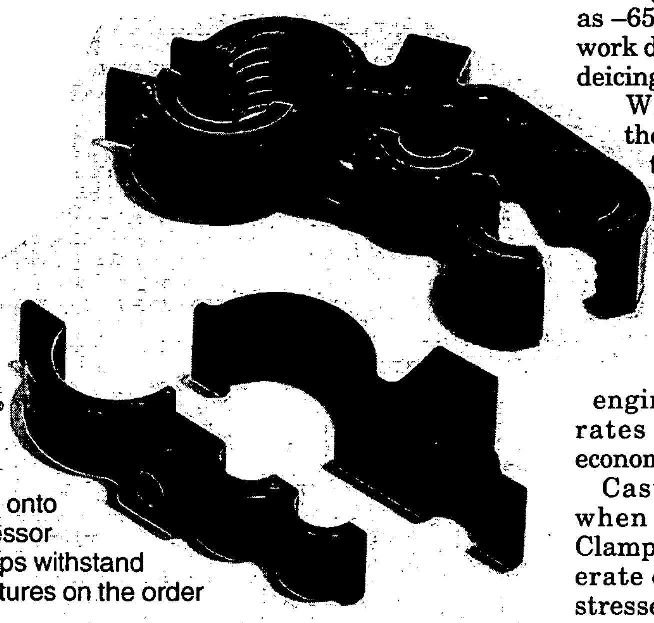
Once formed, parts are polished to a high gloss with conventional muslin wheels. Deburring is done by tumbling parts in vibratory or rotating deburring equipment with an abrasive media, tumbling detergent, and water. Lapping is performed on a flat, granite surface with a wet/dry abrasive paper wetted with a light machine oil. Crocus cloth for final lapping gives a finer finish. A higher polish comes by additional lapping with Kraft or tablet paper.

Physical property comparisons

PROPERTY	CAST ALUMINUM, 6061-T4	TPI VESPEL® TP-8549	PI VESPEL® ST-2010
Spike temperature, °F	600	450	635
Continuous temperature, °F	500	400	500
Tensile strength, RT, ksi	45	35	9.8
Tensile strength, 500°F, ksi	—	NA	3.7
Tensile modulus, RT, ksi	10,300	2,000	400
Tensile modulus, 500°F, ksi	—	NA	—
Specific gravity, gm/cc	2.7	1.39	1.38

Relative comparisons of PI composites to cast AL and Ti

PROPERTY	CAST ALUMINUM, 6061-T4	TPI VESPEL® TP-8549	PI VESPEL® ST-2010
Creep (bolt)	Poor	Poor	Good
Fatigue strength	Poor	N/A	N/A
Machining cost	Low	Low	Low
Mold tooling cost	Low	High	Low
Weight	Poor	Best	Best
Dampening	Good	Good	Good
Friction	Poor	Best	Best
Stealth	Poor	Good	Good



Double and triple tube clamps for an aircraft engine are made from reinforced Vespel® CP. They attach hydraulic, hot air, and electrical lines onto the engine compressor housing. The clamps withstand operating temperatures on the order of 500°F.

the engine exterior and temperatures as low as –65°F. Finally, the clamp material must work despite moisture, saltwater, and hot or deicing fluids.

What complicates matters is that there's often not much space allotted for tube clamps, particularly in military engines. A small clamp cross section is important to keep weight down. And because clamps are last on the list during development, designers may pick one material over another based solely on shorter lead times.

There might be up to 140 clamps per engine of 30 different designs. At build rates of one to 40 engines monthly, economies of scale are tough to realize.

Cast-aluminum tube clamps are used when temperatures and loads permit. Clamps built from cast titanium better tolerate elevated temperatures and higher stresses. Polyimide composites can fill the niche between these two extremes. And in the case of aluminum tube clamps, polyimide composites are preferred because they

LAMINATES VESPEL® CP-8010	SMC VESPEL® CP-0301	SMC WITH LAMINATE PLY	CAST TITANIUM, 6-4
635	635	635	1,100
500	500	500	800
84.5	50	50 to 84.5	170
84.5	47	47 to 84.5	125 (at 600°F)
8,800	6,800	6,800	16,500
8,800	6,600	6,500	—
1.54	1.54	1.54	4.5

LAMINATES VESPEL® CP-8010	SMC VESPEL® CP-0301	SMC WITH LAMINATE PLY	CAST TITANIUM, 6-4
Good	Better	Better	Best
Good	Good	Good	Best
Medium	Medium	Medium	High
Low	Low	Low	Medium
Good	Good	Good	Worst
Best	Best	Best	Poor
Good	Good	Good	Poor
Best	Best	Best	Poor

are lighter, tolerate elevated exterior engine temperatures, and better dampen vibration.

Making the switch

Conventional wisdom suggests that metal parts are more economical to implement than their composite equivalents. But designers must consider not only material costs, but the component's intended mission and lifetime.

Take filled thermoplastic and thermoset polyimides, for instance. Their spec sheets show them to be a natural fit, yet they fall short for several reasons.

Low volumes make it difficult to amortize the costly injection molds needed for thermoplastic parts. Tooling costs are lower for thermosets, but these materials lose strength at higher operating temperatures. And both materials have marginal stiffness.

Polyimide laminates are another potential replacement for fatigue-prone clamps. Polyimide laminates have superior tensile strength and better resist fatigue. And they are much lighter and stealthier than aluminum — an added bonus for military applications.

Tooling for laminates costs less than complex injection molds because they are basically rectangular forms to build plates from which the clamp is machined. Alternatively, forming laminates with compression molds let designers increase directional *X-Y* plane tensile and flexural properties of the clamp by orienting reinforcement plies parallel to the tube surfaces. Compression molds cost about as much as molds for casting metal. Moreover, and even with custom layups, the cost of compression-molded products is on par with cast metals.

Still, polyimide laminates have some shortcomings. For one, they can delaminate from fatigue. Furthermore, although the directional *X-Y* plane tensile and flexural properties of a laminate are ideal for bending, clamps and bolts have widely different coefficients of thermal expansion.

This mismatch increases compressive stress on the polyimide laminate at elevated temperatures. Simultaneously the heat soft-

Changing composite composition to meet specific needs

FILLERS	PROPERTIES	TYPICAL END-USE APPLICATIONS
Unfilled base resin	Maximum strength and elongation, lowest modulus and thermal conductivity, and good electrical properties	Mechanical and electrical parts at elevated temperatures.
15% graphite (by weight)	Enhances inherent wear resistance and improves long-term thermal stability	For lubricated or nonlubricated, low friction and wear applications.
40% graphite (by weight)	Low coefficient of thermal expansion with maximum creep resistance.	Applications in which low thermal expansion is more important than strength (which is slightly reduced).
15% graphite and 10% Teflon® fluorocarbon resin (by weight)	Lowest static friction.	For low friction and wear applications in moderate temperature and PV environments.
15% MoS_2 (by weight)	Best wear performance in dry environments.	For friction and wear applications in vacuum or inert gases.
40% graphite and 15% Teflon® fluorocarbon resin (by weight)	Lowest wear rate in dry service against soft metals.	For low wear applications in "nonlube" conditions against soft metals like aluminum, brass, and bronze
57% graphite and 5% carbon fibers (by weight)	Lowest coefficient of thermal expansion and highest thermal conductivity	Applications in which low thermal expansion and low coefficient of friction are more important than strength.

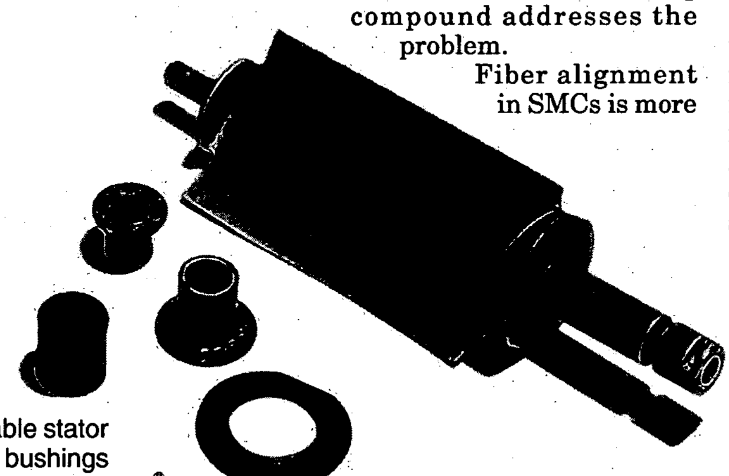
ens the polymer, reducing its compressive modulus along the bolt axis. A lowered compressive modulus can cause material creep which then lets the bolt loosen when the system cools.

One solution is to trade *X-Y* tensile strength for lower thermal growth in the *Z*-direction. Doing so helps lessen the chance of losing bolt preload. Here, a polyimide composite manufactured from a fiber-reinforced sheet-molding compound addresses the problem.

Fiber alignment in SMCs is more random than in laminates made from plies of *X-Y* woven fabric. Because randomness increases the amount of *Z*-aligned fibers within the part, SMCs tend to have a wider scatter of tensile and bending strengths.

To combat lower surface tensile and bending strengths a layup technique can mold a single ply of fabric onto the clamp surface. The additional fabric reduces expansion in the *Z*-direction and also helps damp vibrations.

Composite clamps can be customized to reduce wear between the clamp and the tubing or wire harness. One method is to mold a fabric or compound containing self-lubricating fibers such as Teflon® PTFE onto the surface of the clamp. The approach also eliminates tube coatings and extra parts designed to prevent tube-clamp fretting. ■



Variable stator vane bushings made from Vespel® CP are used in the high pressure section of the compressor in a aircraft engine. The laminate withstands temperatures in excess of 675°F.